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High-Frequency Acoustic Backscatter From the Sea Surface

A Paper Presented at the 107th Meeting of the Acoustical Society of America, 8 May 1984, Norfolk, Virginia

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PREFACE

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Doppler Spread	North Atlantic	Scattering Strength	
Frequency Dependence	Probability Density Function	Shallow Water	
High Frequency		Surface Reverberation	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document contains the slide presentation entitled "High-Frequency Acoustic Backscatter From the Sea Surface," given at the 107th meeting of the Acoustic Society of America on 8 May 1984 in Norfolk, Virginia.

A high resolution scattering experiment was conducted in the shallow waters of the North Atlantic. A narrow beam parametric array, which was rotatable in both azimuth and elevation, was utilized as a broadband high-frequency acoustic

20. Continued:

projector. Acoustic surface scattering data were obtained at normal incidence and low grazing angles (less than 10^{o}) as a function of acoustic transmit frequency and sea state conditions. Meteorologic and oceanographic data were obtained in concert with the acoustic measurements and included wind speed and direction, ocean surface wave spectra and currents, and ocean sound speed. Surface backscattering strength, Doppler spectra (shift and spread), and envelope statistics were some of the measured parameters. It will be shown that the Doppler spectra are approximately Gaussian and the spectral shift could be predicted from Bragg diffraction theory modified by the induced Doppler due to surface currents. The measured Doppler spreads, however, were greater than those predicted by composite roughness theory. At low grazing angles, the surface backscattering strength showed a lack of strong frequency dependence. Yet, at normal incidence under nearly constant sea surface conditions, the surface loss varied 20 dB as the frequency changed from 5 to 80 kHz, which disagrees with physical optics in the high frequency limit.

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HIGH-FREQUENCY ACOUSTIC BACKSCATTER FROM THE SEA SURFACE

INTRODUCTION

A high frequency acoustic boundary reverberation experiment has been conducted in the shallow waters of the North Atlantic. The experiment was jointly performed among several Naval centers and academic institutions, including NORDA; FWG, Kiel, Germany; the University of Rhode Island; City College of New York; and NUSC.

In a shallow water environment, propagation under refractive or nonrefractive conditions generally involves reflection and scattering from the ocean boundaries. Interaction with the ocean boundaries generally occurs at low grazing angles; and, because of the scarce and often conflicting backscatter data that have been obtained previously, a primary objective of the experiment was to determine the statistical characteristics of the surface reverberation. An attempt was also made to measure the normal incidence backscatter and interpret these data in terms of the ocean wave parameters and, if present, near-surface bubble layer thickness and volume scattering strength. Bottom backscattering measurements made during this experiment are described in a companion paper [1].

Presented in this paper are some of the envelope statistics, scattering strengths as a function of frequency, spectral characteristics of the surface reverberation, and surface wave parameters. As will be seen, it was equally important to measure the oceanographic conditions and statistics of the ocean surface for subsequent modeling of the acoustic data.

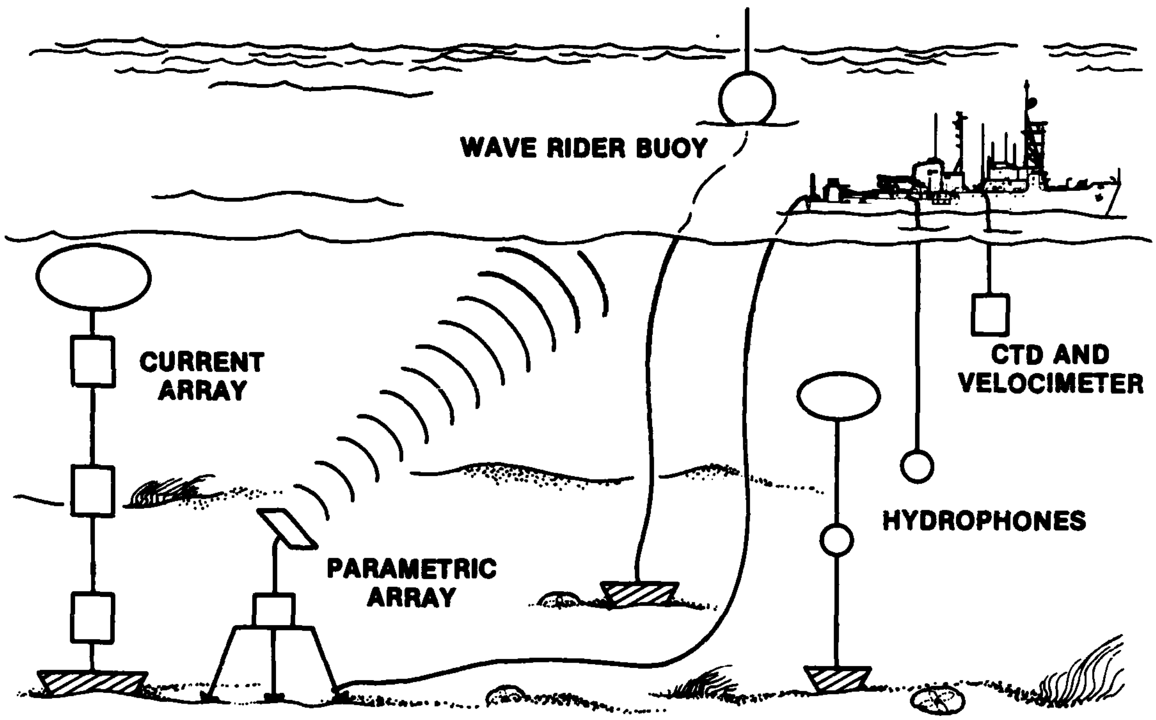

Figure 1. Sea Surface Backscatter Experiment

ACOUSTIC AND OCEANOGRAPHIC MEASUREMENTS

A parametric array (figure 1) was mounted on the top of a 7 m high platform and was projected at the sea surface at angles of normal incidence and grazing angles down to 2°. The projector was also rotated in azimuth to obtain acoustic backscatter for different orientations to the surface wave directionality. A wave rider buoy was used to collect ocean wave statistics, including directionality throughout the experiment. Wave statistics were also obtained at normal incidence backscatter by an acoustic inversion technique developed previously [2]. Both wave measuring techniques were limited to resolving surface wavelengths greater than approximately 1 m. The near surface current array was used to obtain estimates of the surface current magnitude and direction. For in-situ ray arrival determination and subsequent propagation loss prediction, conductivity, temperature, and depth measurements were performed periodically during the acoustic experimentation.

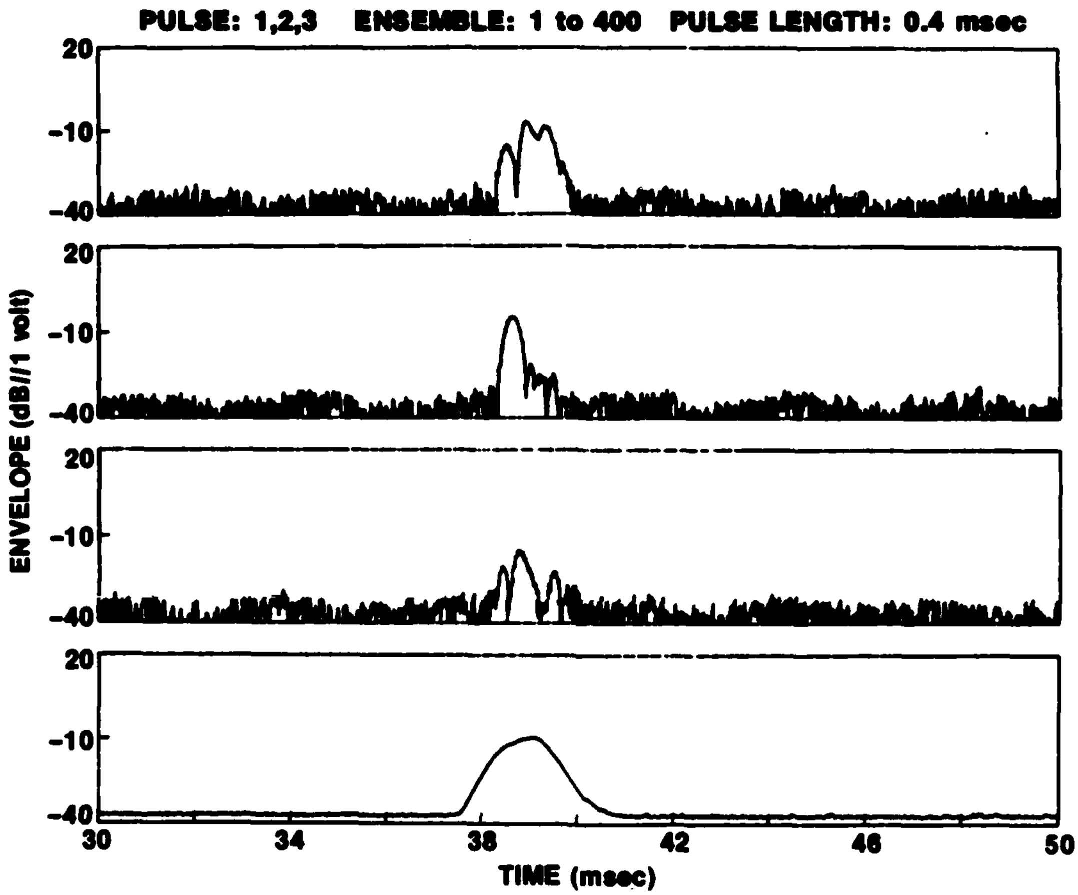

Figure 2. Normal Incidence Surface Backscatter Envelope

NORMAL INCIDENCE SURFACE BACKSCATTER

Acoustic backscatter from the sea surface was obtained at normal incidence using a parametric array, which also functioned as a conventional receiver. The insonified area on the surface was on the order of one square meter. The transmitted pulses were of identical shape and phase having the same zero time reference for each. The upper three plots in figure 2 show the envelope time history of three individual received pulses for a frequency of 20 kHz and a 0.4 ms pulse length. Fluctuations in received amplitude on a pulse-to-pulse basis are a result of the time variation in the average number of specular points on the surface times the average curvature of these points as predicted from either geometrical or physical optics theory. The bottom figure is the ensemble average of 400 pulses. The time dispersion in the ensemble is approximately 3 ms, which is directly related to the vertical height variation in the surface wave motion.

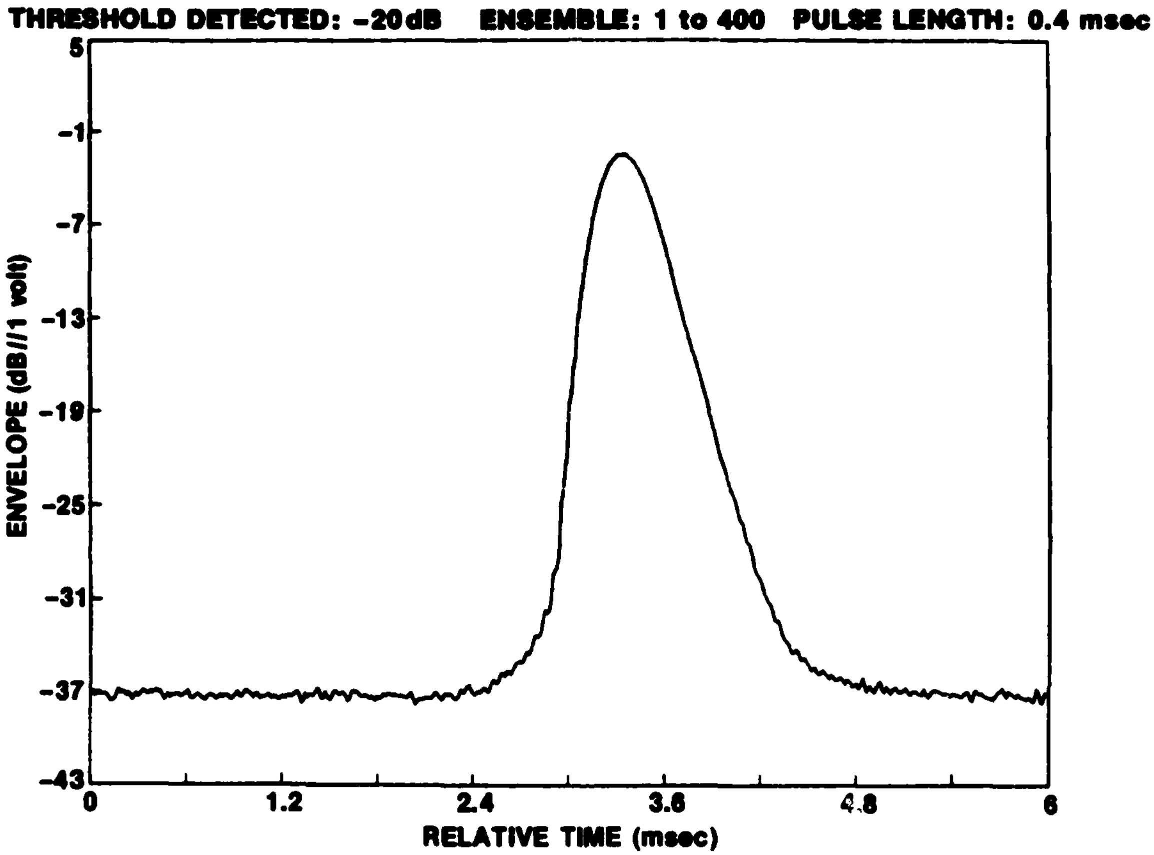

Figure 3. Threshold Detected Surface Backscatter Envelope

In order to use acoustic inversion techniques to measure the ocean wave parameters, near-surface bubble scattering layer thickness, and volume scattering strength, 0.4 ms pulses were transmitted and ensemble averaged. The 0.4 ms pulses would resolve bubble layer thickness to 0.75 m. A threshold level of -20 dB was set to determine the onset of surface backscatter and 400 pulses were ensemble averaged. The result is shown in figure 3 for a transmitted frequency of 20 kHz. There is no clear evidence of a persistent near-surface bubble scattering layer, which would show as a precursor to the onset of the surface backscatter. The minimum detectable volume scattering strength was -47 dB.

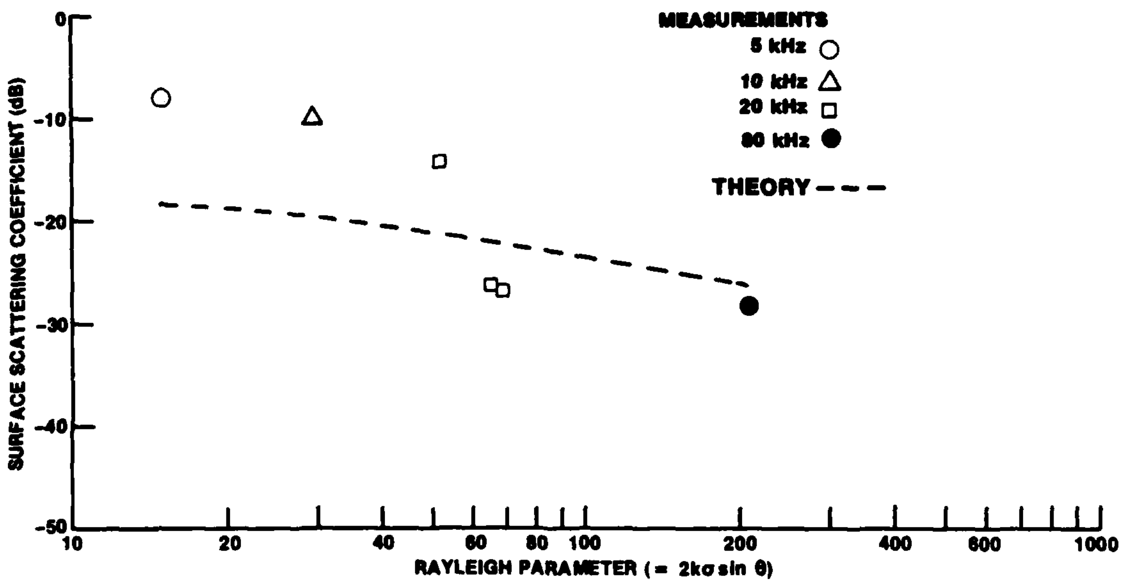

Figure 4. Surface Scattering Coefficient Vs.
Rayleigh Parameter at Normal Incidence

The normal incidence surface scattering coefficient was calculated using a physical optics approach [3] and is shown in figure 4 as a function of the Rayleigh parameters for several acoustic frequencies and two sea state conditions. At these large Rayleigh parameters, the acoustic intensity is independent of both frequency and root-mean-square wave height and is solely a function of the mean squared slope and insonified area. It can be seen that there is considerable discrepancy between the measured values and the theoretical prediction. The coefficient of variation for some of these data sets was greater than 52.5%, which indicates that the insonified area was smaller than the surface correlation length.

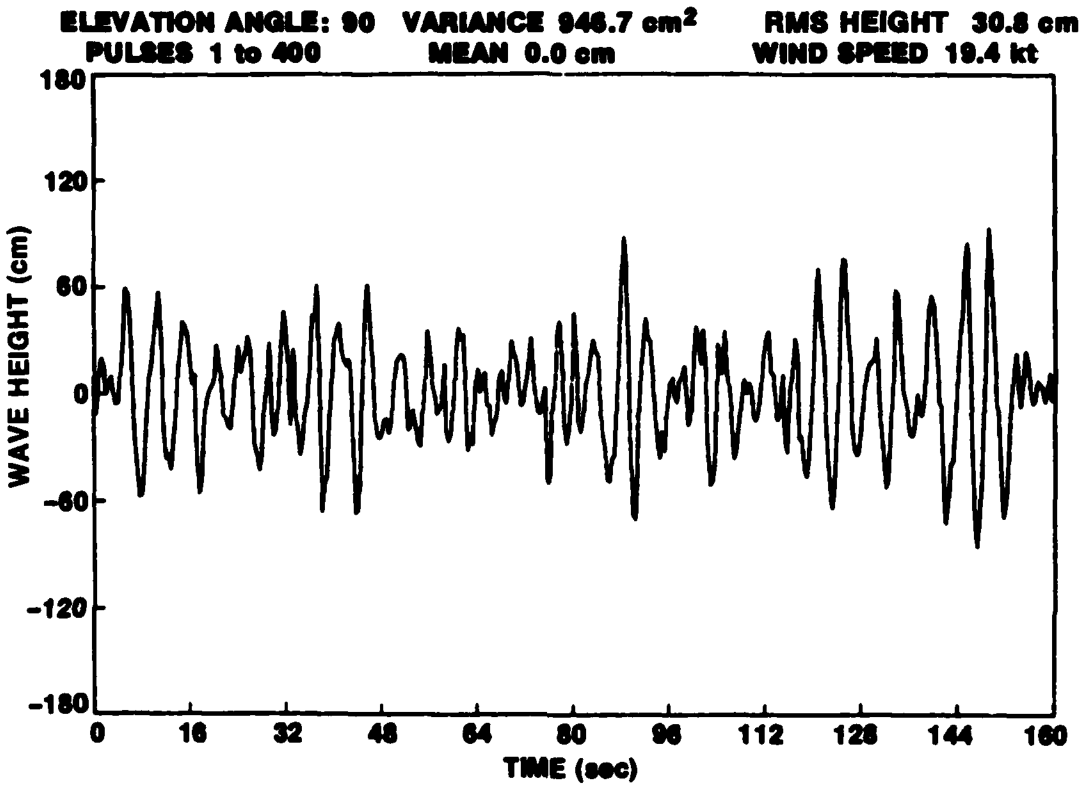

Figure 5. Wave Height Vs. Time

ACOUSTIC WAVE HEIGHT MEASUREMENTS

The time varying wave height (figure 5) was calculated from the travel time associated with the threshold detected surface backscatter and the mean sound speed. The surface height was sampled at a rate of 2.5 times a second, which was the repetition rate of the transmitted pulses. The standard deviation of the time varying wave height was 30.8 cm.

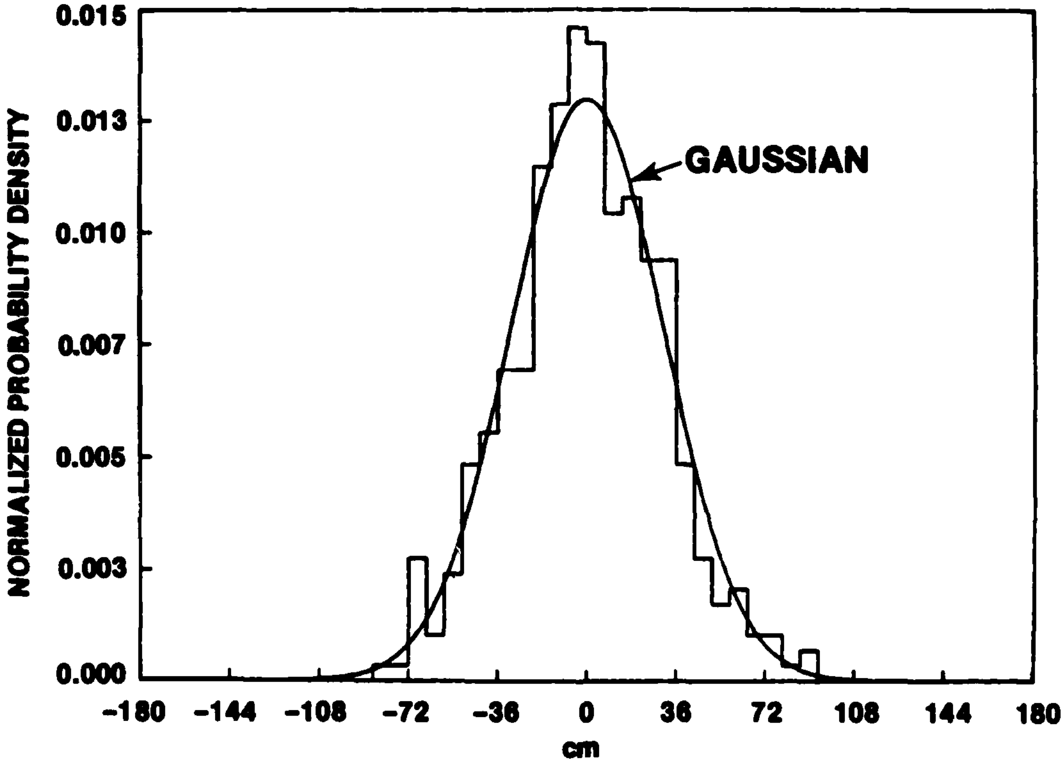

Figure 6. Wave Height Probability Density Function

The probability density function (PDF) for the previous wave height time history is shown in figure 6 as a histogram normalized by its area. The solid curve is Gaussian with zero mean and area one. Note that the measured PDF is slightly skewed toward negative heights reflecting the fact that waves spend more time as troughs than peaks.

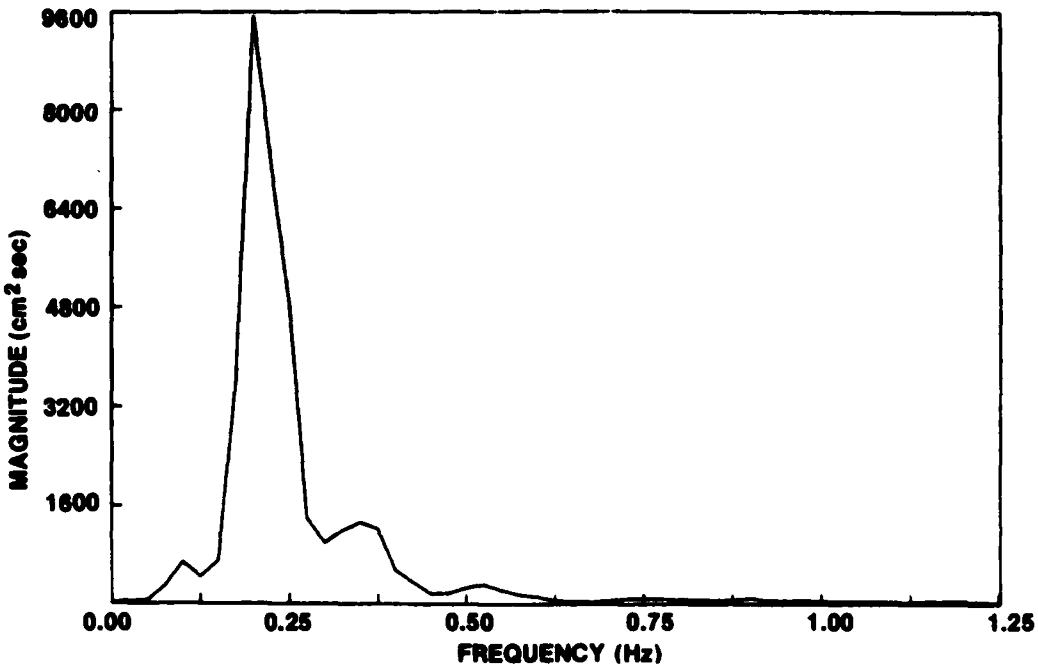

Figure 7. Surface Wave Spectrum

The surface wave spectrum was calculated from the wave height time series derived from the thresholded acoustic signals. Comparisons of the mean squared wave height obtained from this acoustic technique and the wave rider buoy showed very good agreement. This verification was important because the wave rider buoy data were obtained on an hourly basis throughout the experiment. The peak of the spectral energy shown in figure 7 occurs at a frequency of 0.2 Hz and the root mean square height was 30.8 cm. A further comparison with a Pierson Moskowitz [4] spectrum shows that for this wind speed, the sea was not fully developed since the peak frequency should be at 0.14 Hz and the corresponding wave height should be 53 cm. This points out the necessity of measuring surface statistics during the acoustic measurements and not relying on local wind speeds as an indirect indicator of sea conditions.

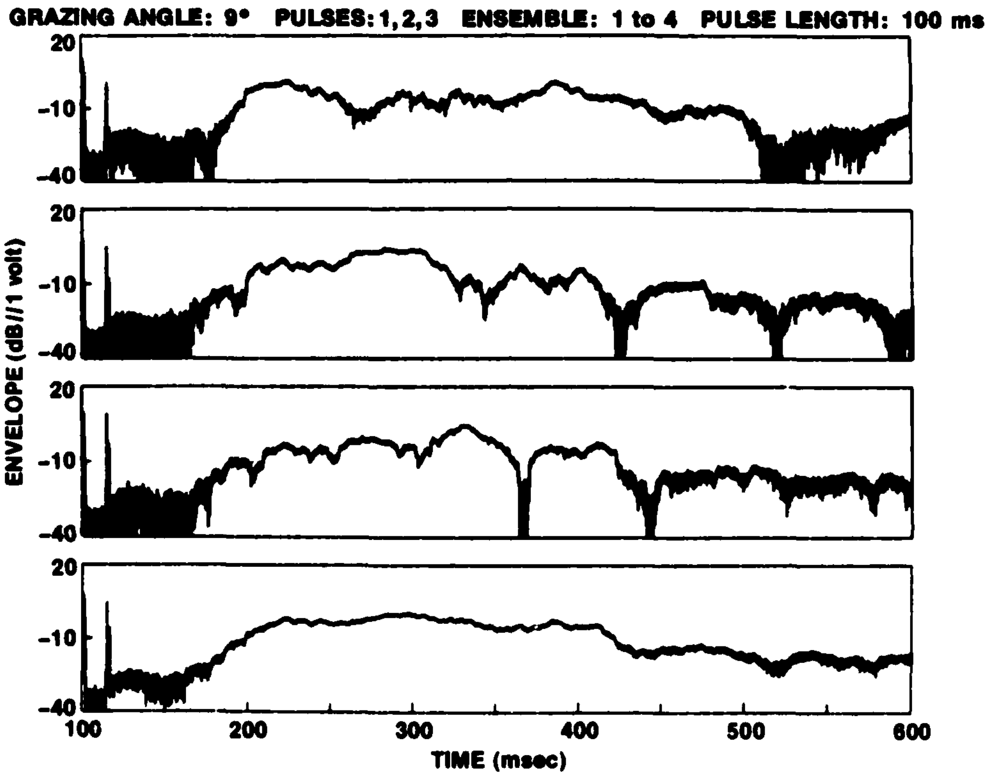

Figure 8. Surface Reverberation Envelope at a 9° Grazing Angle

SURFACE REVERBERATION AT A LOW GRAZING ANGLE

A low grazing angle example of surface reverberation at 20 kHz is representative of the time dispersion and amplitude variability commonly observed for backscatter from the sea surface. The top three plots in figure 8 are received levels from consecutive 100 ms pulses obtained with a repetition period of 3.5 s. The bottom plot is an ensemble average of the first four pulses in the sequence. As expected, the averaging process reduces significantly the amplitudinal interference effects seen in the individual returns. The 9° surface grazing angle, which corresponds to the MRA of the parametric source, occurs at a time of approximately 230 ms in this data set. Because of the existing sound speed conditions, the MRA was downwardly refracted by 4° before intersecting the sea surface.

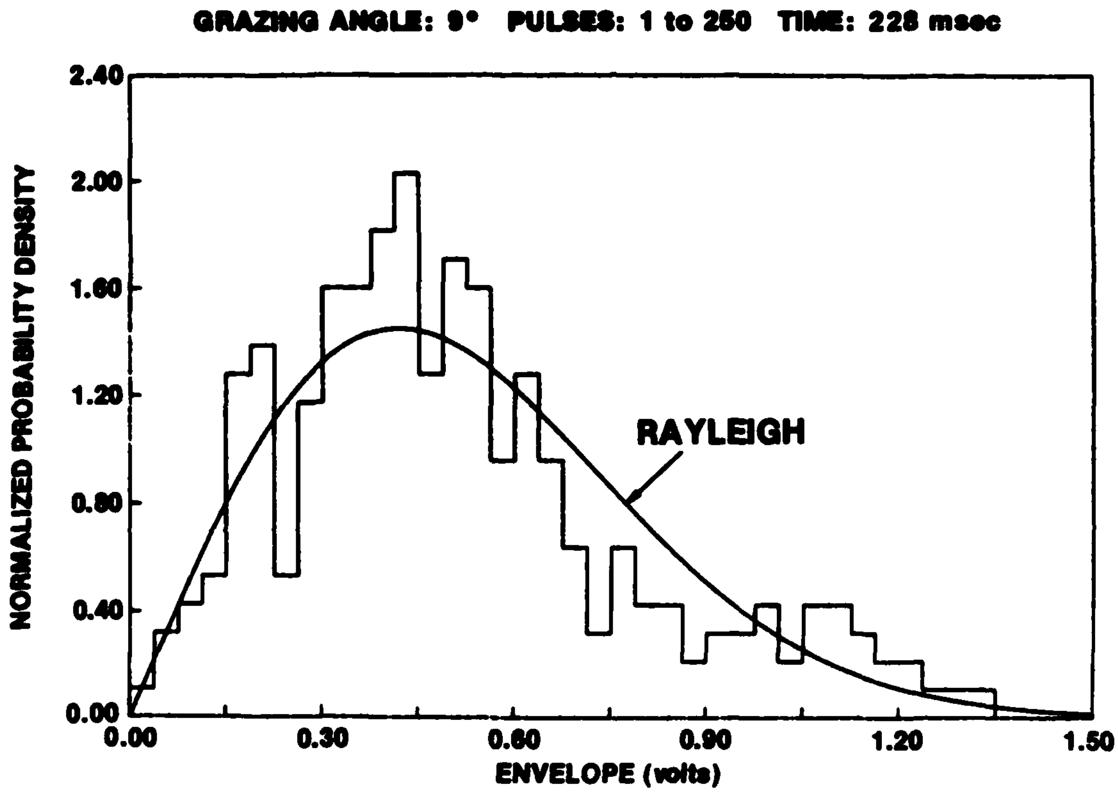

Figure 9. PDF of Backscattered Levels for a Fixed Travel Time

The PDF of the variations in the envelope of the backscattered levels have been computed from the surface reverberation measurements. An example of a 9° grazing angle (figure 9) was obtained at 20 kHz from 250 levels associated with the travel time of the MRA. Theoretically, a Rayleigh density is predicted for the envelope fluctuations of incoherently scattered energy. The measured coefficient of variation for this example is 58%, which compares favorably with the 52% expected for the Rayleigh density function. Additional statistical tests are being conducted on these data. PDFs for single ping statistics have also been computed.

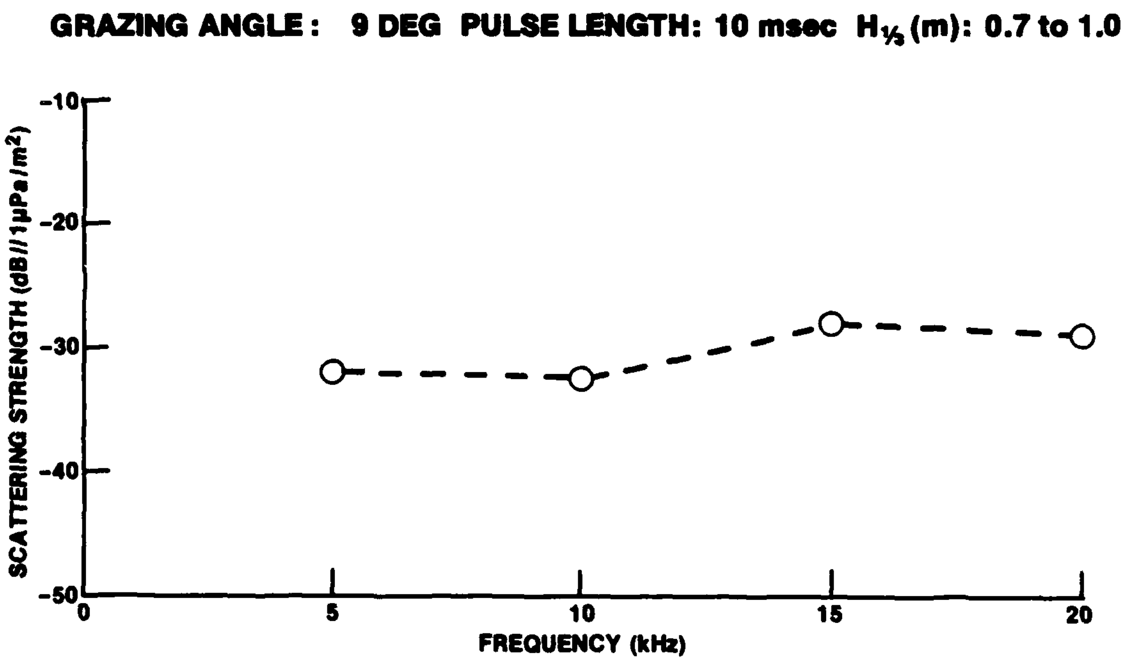

Figure 10. Frequency Variation of Surface Scattering Strength at a 9° Grazing Angle

Surface reverberation was measured as a function of frequency in 5 kHz intervals from 5 to 20 kHz. The grazing angle was held constant at 9°. During the measurements, the significant wave height varied from 0.7 to 1.0 m. It can be seen from figure 10 that the scattering strength has less than 2.5 dB variation when the frequency is varied over two octaves. The average scattering strength is approximately -30 dB. A comparison with Chapman and Harris' semiempirical equation for scattering strength would show 7 dB variation over the same frequency range.

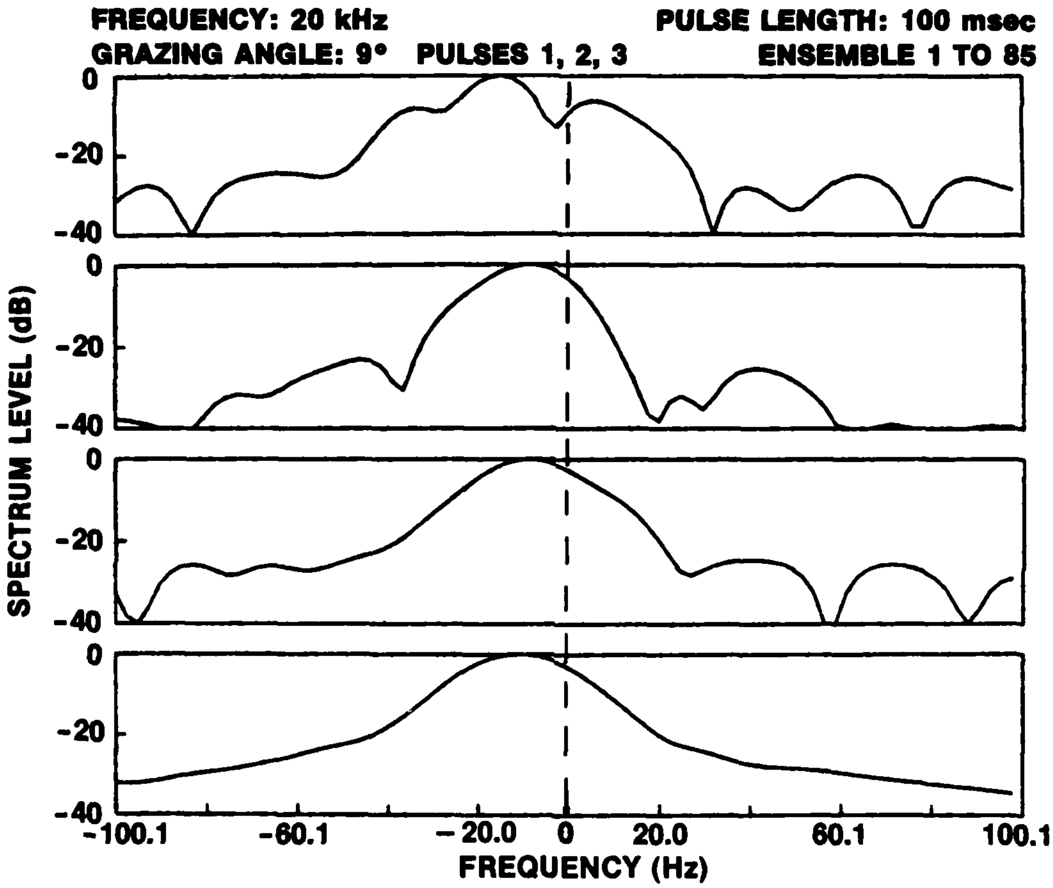

Figure 11. Surface Reverberation Spectra for a 9° Grazing Angle

DOPPLER CHARACTERISTICS OF SEA SURFACE REVERBERATION SPECTRA

Shown in figure 11 are sea surface reverberation spectra for a 20 kHz transmit frequency, a 100 ms pulse length, and a 9° grazing angle. The zero on the frequency axis corresponds to the energy at the transmit frequency. The upper three spectra demonstrate the variability in the spectral content for three consecutive pulses, each implying a slightly different velocity distribution of sea surface scatters. The bottom spectrum is an ensemble average of 85 individual spectra, and exhibits an approximately Gaussian shape. Note that the average spectral peak of the surface reverberation is downshifted 12 Hz from the transmitted frequency and the energy is spread in frequency over a bandwidth of approximately 24 Hz.

$$f_D = -\left[\cos\Phi \left(\frac{g \cos \Psi}{\pi \lambda} \right)^{1/2} + \frac{2\, v_s \cos \alpha \cos \Psi}{\lambda} \right]$$

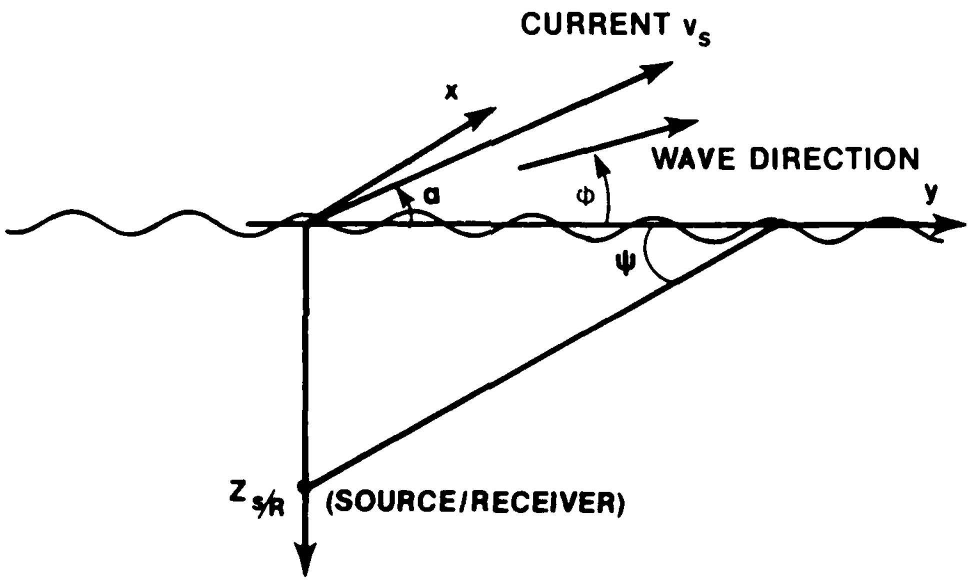

Figure 12. Theoretical Doppler Shift Prediction

The Doppler shift of the average spectral energy can be predicted from resonance theory backscatter as suggested by Bass and Fuks [5,6] and Kur'yanov [7]. In figure 12, we have taken into account the directions of the surface wave propagation and surface current relative to the orientation of the source/receiver. The Doppler shift is predicted from the surface wavelength component that resonates with the acoustic wavelength for a given grazing angle and from the surface current component. It's interesting that the Doppler shift is independent of surface amplitude; however, this must be taken into account when predicting the Doppler spread.

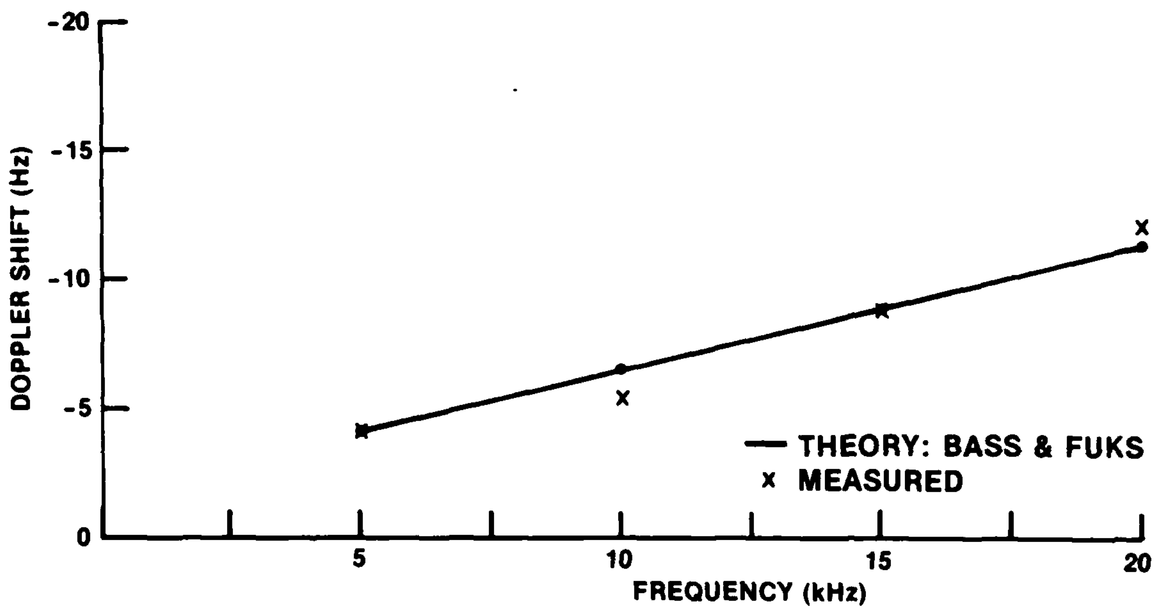

Figure 13. Surface Reverberation Doppler Shift: Theory and Measurement

Doppler shift, measured from the surface reverberation spectra, is plotted versus transmit frequency in figure 13. The theoretical shift (calculated from the previous equation, and the measured geometric, oceanographic, and acoustic parameters) is plotted as the solid line. It is evident that the measured shifts are well described by the theoretical equation.

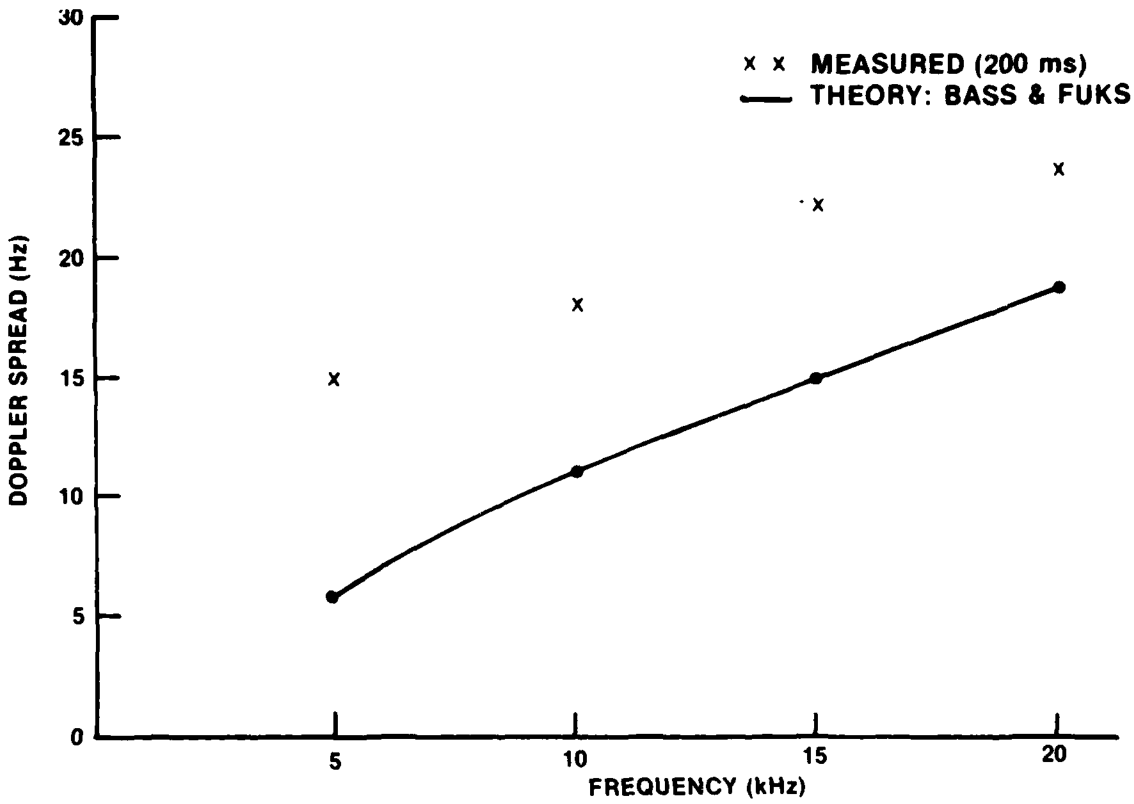

Figure 14. Surface Reverberation Doppler Spread: Theory and Measurement

Doppler spread (shown in figure 14) was measured from the Doppler reverberation spectra between the 10 log 1/E points below the spectral maximum. The theoretical solid curve was derived from an expression for spectral spread by Bass and Fuks [6]. The predicted spectral spread of the sound backscattered from the sea surface is inversely proportional to acoustic wavelength and orbital period for the maximum surface wave energy density. As the signal frequency increases, the observed spectral spread increases as predicted by the expression. The theoretical spectral width, however, is only approximately 40-60% of our measured width. Bass and Fuks compared their spread equation with measured acoustic data and observed the same result.

SUMMARY

- DOPPLER SHIFTS PREDICTED BY BRAGG DIFFRACTION THEORY WITH SURFACE CURRENT
- DOPPLER SPECTRA WERE GAUSSIAN
- DOPPLER SPREADS WERE GREATER THAN PREDICTED BY COMPOSITE ROUGHNESS THEORY
- NORMAL INCIDENCE BACKSCATTER DATA DISAGREES WITH PHYSICAL OPTICS HIGH FREQUENCY LIMIT THEORY
- LACK OF STRONG FREQUENCY DEPENDENCE (5-20 kHz) OF SCATTERING STRENGTH AT LOW GRAZING ANGLES
- ACOUSTIC INVERSION TECHNIQUES SUCCESSFULLY OBTAINED OCEAN WAVE PARAMETERS AND STATISTICS

Figure 15. Surface Reverberation Summary Highlights

SUMMARY AND CONCLUSIONS

The experiment has verified that the Doppler shift of ensemble averaged surface reverberation spectra can be predicted from resonance backscatter theory and that the ensemble average exhibits an approximately Gaussian shape. The major conflicts between theory and measured data occur in the prediction of (1) Doppler spread at low grazing angles and (2) the absolute levels of backscattered intensity as exemplified by the normal incidence data. The high values of scattering strength and lack of strong frequency dependence cannot be predicted from current backscatter composite models. This can also be seen from the Doppler spread predictions that underestimate the bandwidth of the reverberation Doppler spectra. As an aside, it is encouraging to see that acoustic inversion techniques can be used to obtain important statistical characteristics of ocean waves.

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